

Chapter 1

Ubiquity and antiquity

Finding aluminum as metal on the surface of the Earth today is not difficult, but it wasn't always that way. Because of its affinity for other elements, aluminum in the Earth's surface is always found combined with other elements to form clays, minerals or even gems, but not as a metal. The discovery of a way to make aluminum metal changed that. Many modern buildings have aluminum windows, doors and roofs. Commercial and military aircraft are mostly made of aluminum. Thousands of miles of aluminum wire are strung between electrical power transmission towers. Aluminum beverage cans and bits of aluminum packaging foil can be seen lying on the ground around the world – and pieces of laminated aluminum-foam panels can be found washed up on remote beaches. Just as scientists found a layer in the Earth's surface containing an excess of the iridium, an element commonly found in meteorites, marking a time about 65 million years ago that separates the Mesozoic Era from the Cenozoic Era, so too will scientists in the distant future find a layer marking a period dominated by human impacts, including climate change, new ecosystems, landscape modifications and the presence of aluminum metal on the surface of the Earth. That era already has a name – the Anthropocene.

Copper, lead and tin have been mined, smelted and worked for thousands of years, but aluminum has been commercially produced only since the late 19th century. Despite that late start, aluminum production has surpassed other nonferrous metals in both volumetric and tonnage terms. In 1900, the total worldwide annual output of aluminum was 8,000 tons. By 1913, it was 65,000 tons. By 1920, it was 128,000 tons. By 1938, it was 537,000 tons. By 1946, it was 681,000 tons. And by 1997, about 22 million tons of primary aluminum was produced worldwide, along with 7 million tons of recycled aluminum.¹ “The historian who would trace the story of aluminum has a comparatively easy task,” Junius D. Edwards wrote in his book “Aluminum and its Production” in 1930. “It is not referred to in the writings of the ‘ancients,’ nor in classical records; aluminum is a product of the present age.... Many now living have quite literally grown up with the metal.”²

Aluminum is the third most abundant element in the Earth's crust after oxygen and silicon. It is the most abundant metal but it wasn't isolated until the 19th century because it occurs naturally only in compounds and is difficult to separate. Aluminum is located in Row 2, Group 13 of the periodical table of elements. Elements in the same column typically have similar properties but because boron, the top element in the

column, is very different from the other elements in the column, the group is referred to as the aluminum family.³ Aluminum's atomic number is 13, its atomic weight is 26.98154, and its melting point is 660.37 degrees Celsius.⁴ The most abundant metallic element found on Earth and the Moon, aluminum makes up more than 8% of the Earth's surface by weight. Nearly all rocks contain aluminum in the form of aluminum silicate minerals. Aluminum as a metal is protected from corrosion by the natural formation of an oxide film which is self-limiting at about 5 nanometers in dry air at room temperatures.⁵ It is never found in nature in a pure metallic form, as is copper and iron. Aluminum combines with other elements, particularly oxygen, to form an extremely hard oxide called alumina. When combined with traces of other elements, it can take the form of gems, such as rubies and sapphires.⁶

Aluminum's light weight plays a role in plate tectonics – the theory that explains the formation of continents and their movement across the Earth's surface. In the 19th century, Eduard Suess proposed names for geochemical divisions to describe the Earth's crust, and this model has been confirmed in modern times by petrographic, gravimetric and seismic evidence. The geochemical term for the upper layer of the Earth's crust is SiAl, which stands for rocks rich in silicates and aluminum – elements that are absent in the wide oceanic basins. The geochemical term for the lower layer of the Earth's crust is SiMa, which stands for rocks rich in magnesium silicate minerals that make up most of the ocean floor – the basalt layer of the Earth's crust. SiMa is more dense than SiAl, explaining why continental plates move above oceanic plates. The nickel-iron core of the Earth is sometimes referred to as NiFe, based on the elemental symbols for nickel and iron.⁷ The interaction of the SiAl tectonic plates with the SiMa plates is believed to be responsible for the creation of sapphires and rubies, which are made of aluminum oxide, also known as the mineral corundum, the third hardest material known after diamonds. Trace amounts of elements such as iron, titanium, chromium, copper or magnesium present during formation are responsible for the color of a sapphire.⁸

Aluminum also is naturally found in silicate minerals or as aluminum oxide, in a different form than corundum known as alumina, in certain kinds of sedimentary rocks of the laterite or bauxite family. Bauxite, the raw ore that is mined for aluminum production, is a mixture of the hydroxides of aluminum along with impurities such as oxides of iron, titanium and silicon. Bauxite is not a rare ore and is widely found in the United States, the Caribbean, Europe and especially in Australia, Guinea and northern South America.⁹ The word bauxite is applied loosely to any aluminum-bearing substance found in nature in which alumina is the largest single constituent.¹⁰ Commercial grade bauxite should contain at least 40% alumina. It is usually mined by open-pit method and sent to a refinery to produce alumina.¹¹

Bauxite contains hydrated oxides of aluminum, including gibbsite, boehmite and diaspore, as well as hydrated oxides of iron and silicate minerals, kaolin and moisture. The most desirable aluminum mineral for commercial purposes is gibbsite. The least desirable is boehmite and diaspore. Bauxite is created by the long-term weathering or chemical alteration of host rock, dating from one million to hundreds of millions of years ago. Most bauxite is found in tabular, near-surface deposits in tropical areas or areas that were once tropical. With the exception of Australia and southern Europe, most of the world's bauxite is found in remote areas and often in countries that are relatively unstable and economically undeveloped.¹²

Bauxite deposits worldwide can be divided into four broad categories – blanket, pocket, detrital and interlayered deposits. Blanket deposits are usually found in horizontal layers near the surface with overburden ranging from 2 inches to 30 feet, and they often range from 15 to 20 feet thick and up to several miles long. Some of the world's larger blanket deposits are found in South America, Australia, West Africa and India. Pocket deposits are found in geological depressions with little overburden and are common to Jamaica and southern Europe. Detrital deposits are geologically older and can be found in Georgia and Alabama. Interlayered deposits are often found buried under a heavy layer of overburden and tend to be compacted. Interlayered deposits are found in the U.S., Guyana, Surinam, the former-Soviet Union, China, Ireland and southern Europe.¹³

Aluminum in ancient times

Anthropologists sometimes divide ancient times into ages defined by their use of metal. Copper, which can be found in pure form on the Earth's surface, has been in use around the world for more than 7,500 years. Bronze, an alloy of tin and copper, has been in use for around 4,000 years. Iron and steel have been in use for more than 3,000 years. But the aluminum age didn't begin until a suitable method for commercial production was discovered in 1886.¹⁴ While not available as a metal, aluminum played an important role in human culture in mineral form. Together, silica and alumina make up about 75% of the Earth's crust and are present in many of the minerals found in clays. Primary residual clays form when feldspathic rocks are exposed to weathering for long periods of time.¹⁵ The earliest uses of aluminum by humans can be traced back to approximately 5000 B.C. when people in Iraq made fine pottery from clay that consisted largely of a compound containing aluminum.¹⁶

Kaolin, also known as China clay or white clay, contains much less iron oxide and has been used for thousands of years for vitrified white ware, paper sizing and coatings. A good source of kaolin existed in China at Kaolin Mountain, and by 600 A.D. a large ceramic complex was established nearby at Jingde Zhen. Over time, the name kaolin

became part of ceramics terminology. Kaolin today typically consists of 58% silica and 29% alumina.¹⁷ Unusual reports of objects fashioned from aluminum metal have been made over the years. Analysis of a curious metal ornament found in the tomb of Chou-Chu, a military leader in the third century B.C. in China, was found to be 85% aluminum. It remains a mystery how it was produced.¹⁸ In the first century A.D., according to the Roman author Pliny The Elder, a master craftsman presented the Roman emperor Tiberius with a very light and beautiful goblet made of a silvery metal. The craftsman said he produced the metal from ordinary clay. According to the fable, Tiberius ordered the man's head chopped off and his workshop destroyed to prevent a drop in gold and silver prices.¹⁹

Egyptians and Babylonians used aluminum compounds in various chemicals and medicines as far back as 2000 B.C. Egyptians reportedly used the coagulant alum as early as 1500 B.C. to reduce the visible cloudiness or turbidity in water.²⁰ The western desert of Egypt was a major source of alum substitutes in antiquity.²¹ In the first century A.D., Pliny the Elder referred to a substance as alumen in his book "Historia naturalis," a scientific source book used through the Middle Ages.²² The substance was similar to stuperia, as described by the Greek physician Dioscorides about the same time. The alumen of the ancients was not always the same as the alum of the modern age. The ancients knew how to produce alum from alunite, which has been archaeologically attested to on the island Lesbos. That site was abandoned in the 7th century but dated back at least to the 2nd century B.C.²³ Contamination with iron sulfate was greatly disliked, as it darkened and dulled dye colors. Merchants and manufacturers at the time were acquainted with a variety of substances of varying degrees of purity by the names of misy, sory and chalcantum. As alum and green vitriol were applied to a variety of substances in common, and as both were distinguished by a sweetish and astringent taste, writers even after the discovery of alum did not seem to have discriminated between the two salts accurately. The alchemists applied the words misy, sory and chalcantum to alum as well as to iron sulfate, and the name atramentum sutorium, which one might expect to belong exclusively to green vitriol, applied indifferently to both. Various minerals were employed in the manufacture of alum, the most important being alunite, alum schist, bauxite and cryolite.²⁴

Alum, a compound of potassium, aluminum, sulfur and oxygen, was mined in ancient Greece and sold to the Turks, which used the compound to make a beautiful dye known as Turkey red. The Romans used alum since the first century B.C. Alum was also used as an astringent to close open cuts in the skin to start healing and as a mordant to make natural dyes stick to cloth – the mordant sticks to cloth, and the dye sticks to the mordant.²⁵ In the first century B.C., a Roman commander named Archelaus discovered that wood was nearly flame-resistant if it was treated with a solution of alum. He used

the solution to protect his fortifications. The use of alum throughout Europe continued through the 17th century as a tanning agent in the leather industry, for paper sizing in the paper-pulp industry, and in medicine for dermatology, cosmetology, stomatology and ophthalmology.²⁶ Alum was even used as an ingredient in baking powder.²⁷

Alum was imported into England mainly from the Middle East, and from the Papal States for hundreds of years. Its use in England was as a dye-fixer for wool, which was one of England's primary industries. Wool's value increased significantly if dyed. In the 13th and 14th centuries, alum from alunite was a major import from the Gulf of Smyrna in Byzantium and was sold by Genoans and Venetians – it was a cause of war between Genoa and Venice. Alum was sold later by Florence. After the fall of Constantinople in 1461, alunite was discovered at Tolfa in the Papal States. The textile dyeing industries in Bruges, Italy and later England required alum to stabilize the dyes and brighten colors. These sources were unreliable for England, and there was a push to develop a source in England – especially as imports from the Papal States ceased following the excommunication of Henry VIII.²⁸ With state financing, attempts were made throughout the 16th century, but without success until the 17th century. An industry was founded in Yorkshire to process shale, which contained the key ingredient, aluminum sulfate, and this made an important contribution to the Industrial Revolution. One of the oldest historic sites for the production of alum from shale and human urine were the Peak alum works in Ravenscar, North Yorkshire. By the 18th century, the landscape of northeast Yorkshire had been devastated by this process, which involved constructing 100-foot stacks of burning shale and fueling them with firewood continuously for months. The rest of the production process consisted of quarrying, extraction, steeping of shale ash with seaweed in urine, boiling, evaporating, crystallizing, milling and loading into sacks for export. Quarrying ate into the cliffs of the area, the forests were felled for charcoal and the land was polluted by sulfuric acid and ash.²⁹

By 2017, alum was the common name of a specific chemical compound, hydrated potassium aluminum sulfate, and a class of chemical compounds. Alums were useful for a range of industrial processes. They were soluble in water, had a sweetish taste, reacted acidic to litmus, and crystallized in regular octahedra. In alums, each metal ion was surrounded by six water molecules. When heated, they liquefied, and if the heating was continued, the water of crystallization was driven off, the salt frothed and swelled, and an amorphous powder remained. Alums were astringent and acidic. Some alums occurred as minerals. The most important members – potassium, sodium and ammonium – were produced industrially. Typical recipes involved combining alumina, sulfuric acid and the sulfate second cation, potassium, sodium or ammonium. Alum continued to be used as a dye fixative, for purification of drinking water and industrial waste water, to dissolve steel without harming surrounding aluminum or base metals, in

styptic pencils to stop bleeding, for waxes used to remove body hair, as a substitute for pomade to make hair stay up all day, for antiperspirant or antibacterial uses, as a spice or a preservative for fruit and vegetables, as a component of some baking powders, as an additive to dough to make bread whiter, as a flame retardant for cloth, wood and paper, as a component in ceramic glazes, for tanning animal hides, to treat canker sores, as an ingredient to increase the efficiency of vaccines, as a paint pigment, for paper marbling, as an ingredient in children's modeling compounds such as Play-Doh, and for paper sizing by the Japanese.³⁰

By the 15th century, alchemists and metalworkers suspected that some kind of metal existed in alum minerals. It wasn't until the 18th century that scientists could propose at a theoretical level that aluminum existed as a metal, but traditional metallurgical methods used to produce copper and other nonferrous metals could not be used to extract aluminum from its ores.³¹ The search for aluminum began with the alchemists. The introduction of alchemy to Europe can be dated to 1144 with the translation of the Arabic "Book of the Composition of Alchemy" by Robert of Chester. Robert noted in his preface that alchemy was unknown in Latin Europe at the time of his writing. Today, alchemy is defined as a philosophical and proto-scientific tradition practiced throughout Europe, Egypt and Asia that aimed at purifying, maturing and perfecting certain objects, including the transmutation of base metals, such as lead, into noble metals, such as gold. Alchemists also sought to find an elixir of immortality, cures to any disease and the creation of a universal solvent. In Europe, the philosopher's stone was variously connected to all these efforts.³² Much of alchemy in the 12th and 13th centuries evolved from translations of classic works by Aristotle, Hermes and Democritus. By the end of the 13th century, alchemy had developed into a fairly structured belief system, but by the 14th century discourse shifted from philosophical debate to criticism of its practitioners. Dante, Piers Plowman and Chaucer characterized alchemists as thieves and liars, Pope John XXII issued an edict that forbid false promises about transmutation of metals, and King Henry IV of England banned the practice of "multiplying metals."³³

By the end of the 15th century, Theophrastus Bombastus von Hohnheim, also known as Paracelsus, moved alchemy away from occultism and pioneered the use of chemicals and minerals in medicine. "Many have said of alchemy that it is for making of gold and silver," he wrote. "For me, such is not the aim, but to consider only what virtue and power may lie in medicines."³⁴ As Europe moved into the Renaissance period, alchemists found entrepreneurial opportunities related to mining, medical services and the production of chemicals, medicines, metals and gem stones, and they found appointments by royal courts. Many of these appointments were legitimate, but pseudo-alchemical fraud continued through the Renaissance. At that time, the separation between alchemy, chemistry and small-scale assaying and metallurgy was

not as clear as it is today.³⁵ Paracelsus is credited with isolating aluminum oxide – alumina – from alum in the mid-16th century, a major step toward producing aluminum as a metal. He called the material an “aluminus soil.”³⁶ Born in 1493 in a Swiss canton village, the son of a chemist and physician, Paracelsus became a renowned physician, botanist, alchemist, astrologer and general occultist of the Renaissance. While he insisted on using observations of nature over knowledge taken from the classical texts, and for giving zinc its name in 1526, Paracelsus also believed astrology was important to medicine, and much of his theoretical work does not withstand modern scientific thought.³⁷

His wanderings as an itinerant physician and even journeyman miner took Paracelsus through Germany, France, Spain, Hungary, the Netherlands, Denmark, Sweden, Poland and Russia. His travels to Asia and Africa are speculative. He gained a reputation for being arrogant and possibly a habitual drinker, but he also became a folk legend and the subject of bizarre tales – his treatment of villagers during the plague in the 16th century is considered heroic. Paracelsus may be responsible for the creation of the opium tincture laudanum. He was one of the first medical professors to recognize that physicians needed a solid academic background in the natural sciences and chemistry. At the time, surgeons were ranked in the same guild with barbers and butchers.³⁸ While he largely rejected Aristotle’s philosophy, Paracelsus accepted the concept of the four “elements” – water, air, fire and earth. For medical purposes, he also accepted a tripartite alternative of sulfur, mercury and salt, which he believed contained all the poisons contributing to all known diseases. But after spending time as a military surgeon, he called for cleanliness and protection of wounds and for regulation of diets. He died in Salzburg, Austria in 1541.³⁹

The early scientists

The decline of alchemy came with modern science and its emphasis on rigorous quantitative experimentation and a disdain for “ancient wisdom.” Robert Boyle pioneered the use of the scientific method in chemistry in the 17th century. He assumed nothing in his experiments and compiled measurements and descriptions of a diverse nature – including the location of the experiment, the wind conditions and barometric pressure, even the position of the sun and the moon. His approach eventually led to the founding of modern chemistry in the 18th and 19th centuries after the “revolutionary discoveries” of Antoine Lavoisier and John Dalton. A rigid distinction between alchemy and chemistry emerged for the first time by 1720, and by the 1740s alchemy was relegated to the realm of gold making. This movement led to the belief that alchemists were charlatans and that the tradition was nothing more than a fraud.⁴⁰

Paracelsus' isolation of an "aluminum soil" was repeated about 200 years later by the German chemist Andreas Sigismund Marggraff. From that moment forward, the fledgling science community was aware of the possible existence of a metal that would turn out to be aluminum.⁴¹ Marggraff was born in 1709 in Berlin, Germany, and is considered a pioneer of analytical chemistry. He isolated zinc in 1746, using a process that later became economical. He announced the discovery of sugar in beets in 1747 and devised an economical method to extract the sugar.⁴² In 1754, Marggraff discovered that he could use an alkali solution to precipitate a new substance from alum.⁴³ He called the new substance alumina. Most chemists during Marggraff's time believed alumina was an "earth" of a previous unknown metal. The Latin name for alum is "alumen," meaning bitter salt.⁴⁴ Marggraff died in 1782, never having isolated aluminum as a metal.⁴⁵ But he had isolated alumina, the raw material used in today's aluminum smelters. Marggraff's work was continued in 1760 by the French chemist and politician Louis-Bernard Guyton de Morveau, who believed alumina contained a new metallic element. But like Marggraff, he was unable to extract the metal from its oxide.⁴⁶

Born in Dijon, France in 1737, Morveau is credited with developing the first system of chemical nomenclature. He also promoted chlorine for disinfecting buildings. Morveau was elected to the Legislative Assembly in 1792 during the French Revolution and then to the National Convention. Although a member of the right wing, he voted in favor of executing King Louis XVI. He served on the Committee of Public Safety in 1793, when he resigned to devote his time to the manufacture of firearms and establishing a corps of balloonists for the French Revolutionary Army. He was made a baron of the First French Empire in 1811, and died in Paris in 1816.⁴⁷ Proving the existence of a missing metal in the 18th century was difficult – chemical research was still in its infancy, and Mendeleev's periodic table of elements was not published until 1869.⁴⁸ Nevertheless in 1782, Antoine-Laurent de Lavoisier of France recognized the existence of aluminum as an element through logical inference. He described alumina as "the oxide of a metal whose affinity for oxygen is so strong that it cannot be overcome either by carbon or any other known reducing agent."⁴⁹

Lavoisier was born in Paris in 1743. The French nobleman and chemist is widely considered the "father of modern chemistry," although critics note that the title may have resulted from his skill as a self-promoter. Lavoisier often depended on instruments, experiments and ideas of other chemists, but he is also credited with changing chemistry from a qualitative science to a quantitative science. More of a theorist, he recognized the achievements of others' experimental results. Lavoisier recognized and named oxygen in 1778 and hydrogen in 1783, helped construct the metric system and wrote the first extensive list of elements. His discoveries about

oxygen and combustion helped to disprove the predominant phlogiston theory.⁵⁰ Growing up, Lavoisier was influenced by the French Enlightenment. He was awarded a gold medal by the King in 1766 for an essay on the problems of urban street lighting, was appointed to the French Academy of Sciences in 1768, and worked on the first geological map of France in 1769. His work for the French government in 1775 helped improve the quantity and quality of gunpowder for the army. He submitted a new program for reforming chemical nomenclature in 1787, which replaced the classical elements of earth, air, fire and water with 55 substances which at the time could not be decomposed into simpler substances. Those substances came to be called elements.⁵¹

Lavoisier was able to fund his scientific research as a powerful member of aristocratic councils in France, including the Ferme Generale, one of the most hated components of the Ancien Regime. At the height of the French Revolution, Jean-Paul Marat accused Lavoisier of selling adulterated tobacco and other crimes, and Lavoisier was guillotined along with 27 co-defendants on May 8, 1794. When an appeal was made to spare Lavoisier's life so he could continue his research, the judge according to legend replied, "The Republic needs neither scientists nor chemists; the course of justice cannot be delayed." Lavoisier was exonerated by the French government a year and a half after his execution. A statue of him was erected in Paris a century later, and he joins 72 eminent French scientists, engineers and mathematicians whose names are inscribed on the Eiffel Tower.⁵²

While the pursuit of aluminum by alchemists and Renaissance chemists focused on alum, a major discovery in 1799 opened up a new and important route to producing aluminum as a metal. That year, a naturally occurring mineral called cryolite was first described based on observations at Ivigtut and the nearby Arsuk Fjord in southwest Greenland. The name comes from the Greek words "cryo" for "chill" and "lithos" for "stone." The uncommon mineral, sodium hexafluoroaluminate, naturally occurs as glassy, colorless, white-reddish to gray-black prismatic monoclinic crystals. In addition to Greenland, cryolite has been found at Pikes Peak, Colo.; Mont Saint-Hilaire, Quebec; and Miass, Russia.⁵³ Cryolite not only contains aluminum, it also contains fluoride, a key component in the modern industrial process for producing aluminum as a metal. Compounds containing fluoride are common in the Earth's crust, making up about 0.06% to 0.09% by weight. Naturally occurring fluoride is also found as fluorspar, or calcium fluoride, and fluorapatite, or calcium fluoride phosphate. Fluorides are naturally released into the atmosphere by volcanic action, primarily in the form of hydrogen fluoride, a gas. Fluorine compounds found in soils in concentrations from 20 ppm to 1,600 ppm are highly water insoluble and do not readily move through the soil, forming deposits that can be mined.⁵⁴

Jons Jacob Berzelius is believed to have been the first person to produce synthetic cryolite, sodium aluminum fluoride. In a laboratory experiment in 1824, he combined sodium bifluoride with aluminum hydroxide.⁵⁵ Born in Sweden in 1779, Berzelius is considered one of the founders of modern chemistry, along with Robert Boyle, John Dalton and Antoine Lavoisier. He is noted for his determination of atomic weights, experiments that helped determine chemical-combining proportions, demonstrating how electrochemical cells could decompose chemicals in pairs of electrically opposite constituents, and developing the modern system of chemical notation with abbreviated Latin names using one or two letters.⁵⁶ Berzelius discovered or isolated several new elements, including cerium and thorium, and identified silicon and selenium. His lab students discovered lithium and vanadium. He is credited with coining several important chemical terms, including catalysis, polymer, isomer and allotrope, but his meaning for those words was quite different from the modern meaning. Berzelius was the first to make a distinction between organic and inorganic compounds, but he also developed a theory of “vitalism” in 1810, which claimed that living things worked by some mysterious “vital force.” That theory was eventually proven false by experiments performed by Friedrich Wohler in 1828 and Adolph Kolbe in 1845.⁵⁷

Another important change in the pursuit of aluminum metal came as chemists began to use electricity to influence chemical reactions. Sir Humphry Davy of England is credited with being the first scientist to identify aluminum in 1807. In his experiment, he passed an electric arc through a mixture of alumina and potash. The arc freed the aluminum atoms from the oxygen atoms for an instant, but the aluminum immediately fused with iron in the crucible.⁵⁸ Davy did not succeed in isolating metallic aluminum, but he became convinced that alumina contained a metal that he named “aluminium.” Later, he changed the name of this theoretical metal to “aluminum” to correspond with the name of the metal’s oxide, alumina. Sometime later, the name was changed to “aluminium,” as the suffix “ium” matched the suffix used for many other elements, such as sodium, potassium or chromium. The name “aluminium” has become accepted in modern times by many countries around the world.⁵⁹ Aluminium was the accepted spelling in the U.S. until 1925 when the American Chemical Society officially reverted the spelling to aluminum.⁶⁰

Davy was born in Cornwall, England in 1778. The British chemist and inventor became a First Baronet, president of the Royal Society, a member of the Royal Irish Academy and a fellow of the Geological Society. He is recognized for his discoveries of several alkali and alkaline earth metals and his discoveries about the elemental nature of chlorine and iodine. Davy joined the Pneumatic Institution in 1798 to investigate the medical benefits of atmospheric gases. During that time, Davy, James Watt, Samuel Taylor Coleridge and others became regular users of nitrous oxide, and Davy became addicted to the gas.

Davy joined the Royal Institution in February 1801, and soon became a popular lecturer. His lectures sometimes included spectacular and dangerous chemical demonstrations – he once damaged his eyesight in a laboratory experiment.⁶¹ In 1802, while at the Royal Institution, Davy had access to the most powerful electrical battery in the world, and he used it to make the first incandescent light by passing a current through a thin platinum strip. He was a pioneer in the field of electrolysis, splitting common compounds into many new elements and discovering sodium, potassium and calcium. He was the first to isolate magnesium, boron and barium. In 1810, Davy proclaimed chlorine, first discovered in Sweden in 1774, to be an element, and he gave the element its name. In addition to his academic and scientific awards and titles, a crater on the moon was named after him, and a humorous play and a song were written about him. He died in Geneva, Switzerland in 1829.⁶²

Davy's experiment with electricity and alumina was given a critical review in 1858 when Charles and Alexander Tissier published a small book called "Reserches sur l'Aluminium."⁶³ The French industrial chemists noted that Davy had used a battery in his 1807 experiments to produce electrolysis in an attempt to decompose alumina into aluminum, in the same way he had produced sodium and potassium from potash or soda. According to the Tissier brothers, Davy "failed completely" in isolating aluminum as a metal. According to Davy's own notes, they pointed out, his experiments with alumina never produced substantial results and could not be used on a commercial scale.⁶⁴ The historical significance of Davy's discovery was also criticized in a 1903 patent infringement case that went against the Pittsburgh Reduction Co., before the company became Alcoa. "Davy suggested the possibility of producing metal from certain ores conductive in a fused state, and this hint, for it was hardly more, undoubtedly set the chemists and electricians thinking, just as the discovery of Franklin put the idea of the telegraph into the brain of Morse and as the discovery of Watt made possible the inventions of Stephenson and Fulton," Judge Alfred Coxe said in his ruling. "Judged by its practical results, the contribution of Davy was not as valuable as it now appears when read in the light of subsequent achievement. For three-quarters of a century, chemists and electricians all over the world, with Davy's work before them, were endeavoring to find a method of producing aluminum commercially, and they all failed."⁶⁵

Aluminum by chemistry

But rather than focus on the use of electricity, the numerous scientists seeking to coax aluminum out of alumina turned to chemical means for the next half century. In 1825, Hans Christian Oersted, already famous for his discoveries in the field of magnetism, joined the effort to produce aluminum as a pure metal.⁶⁶ Oersted was born in Rudkobing, Denmark, in 1777. The Danish physicist and chemist is best known for his

discovery that electric currents create magnetic fields. He earned his doctorate on metaphysics in 1799 and was later drawn into the study of physics. He became a professor at the University of Copenhagen in 1806 and began to study electric currents and acoustics. In 1820, while giving a lecture, he noticed that a compass needle was deflected when a nearby wire carrying a current from a battery was switched on and off.⁶⁷ To isolate aluminum, Oersted began by passing dry chlorine over a heated mixture of alumina and carbon to create aluminum chloride. He then combined the aluminum chloride with a potassium amalgam and heated the mixture to create potassium chloride and an aluminum amalgam. He then distilled the aluminum-mercury amalgam while keeping it isolated from the atmosphere.⁶⁸ Oersted announced his claim that he had isolated the “metal of clay” to the Royal Danish Academy of Sciences in Copenhagen, Denmark.⁶⁹ “It forms a lump of metal which in color and luster somewhat resembles tin,” he reported.⁷⁰ Oersted, however, was unable to separate the aluminum from the mercury amalgam.⁷¹ He published his discovery in a little known magazine and ended his experiments.⁷² Oersted’s method was repeated in modern times by Klaus Fogh, a chemist at Novo Nordisk, in Copenhagen, and resulted in producing aluminum, thus strengthening the priority claim of Oersted to being the first person to isolate aluminum.⁷³

Davy’s and Oersted’s processes were further refined by the German scientist Frederick Wohler between 1825 and 1845 by substituting potassium for the amalgam and preparing a better way to dehydrate aluminum.⁷⁴ Wohler repeated Oersted’s process in 1825, but the metal Wohler produced was potassium, not aluminum. He worked on the method for two more years, and in 1827 he reacted volatilized aluminum trichloride with potassium to produce small amounts of aluminum.⁷⁵ Wohler found that the more reactive potassium replaced the aluminum, which then appeared as a gray powder. The powder could then be heated to produce a shiny aluminum metal. Wohler’s work made it possible to produce aluminum on demand, but it was very expensive.⁷⁶ In 1845, working at the University of Gottingen, Germany, Wohler succeeded in producing metallic aluminum in larger amounts he described as “big pinheads.” The oxide film covering the globules of metal prevented them from melting and coalescing into one, but Wohler produced enough metal to investigate its chemical properties. He hammered out two of the metallic globules, which together weighed 32 milligrams, and he found the metal’s specific gravity to be 2.50, a close approximation considering the amount of material he had to work with.⁷⁷ That quantity enabled Wohler to establish one of aluminum’s unique properties as a metal – its light weight.⁷⁸

In 1856, Berzelius stated that Wohler was the first to isolate aluminum, not Oersted.⁷⁹ But a century later, chemists repeated their experiments and showed that Oersted had indeed produced metallic aluminum for the first time.⁸⁰ Born in Germany in 1800,

Wohler is best known for isolating urea, thus disproving the theory that only living things can produce inorganic chemicals. He taught at several German universities, was the co-discoverer of beryllium and silicon, and was the first to isolate yttrium and titanium. He also discovered that some meteoric stones contained organic matter. Scientific American in 1882 declared that Wohler deserved the highest honor a scientist could obtain for just two or three of his discoveries, "but the sum of his work is absolutely overwhelming. Had he never lived, the aspect of chemistry would be very different from that it is now." Wohler died in Germany in 1882.⁸¹

For the first half of the 19th century, aluminum was so difficult to isolate as a metal that only small quantities were created by scientists. The metal was more precious than gold and sold for \$4,674 a pound in 1845.⁸² A wonder substance with qualities never before seen, aluminum was lightweight, shiny, resistant to rust and highly conductive. The idea that something like aluminum could come from something as common as clay resurrected the aura of alchemy. But by the 1850s, a method had been found to make a few grams of aluminum at a time, and it began to be used in expensive jewelry.⁸³ In 1854, the French chemist Henri Etienne Sainte-Claire Deville repeated the method used by Wohler to produce aluminum, using aluminum chloride but replacing potassium with sodium, which was easier and less expensive to produce.⁸⁴ At the time, Deville was unaware of Wohler's work 10 years earlier, but the two worked together years later. Deville had developed a new way to manufacture sodium, which benefited his process.⁸⁵ Deville also found a way to make the pinhead-sized lumps previously produced by Wohler to coalesce into lumps the size of marbles. Deville's process became the foundation of the aluminum industry.⁸⁶

Deville announced his discovery to the French Academy of Sciences in Paris, France, in 1854. Whereas Wohler had improved on Oersted's method by leaving out the mercury, Deville had improved on Wohler by substituting sodium for potassium. Deville also discovered that in the course of the chemical reaction, a flux was created made of the readily fusible double salt sodium chloride-aluminum chloride. The presence of the flux helped the aluminum globules melt and coalesce together into pieces the size of marbles.⁸⁷ The resulting metal was more expensive than gold or platinum.⁸⁸ Bars of aluminum produced at Deville's Javel Chemical Works in France were exhibited at the Paris Exposition in 1855, which introduced the metal to the public for the first time.⁸⁹ The "silver made of clay" created a furor. Emperor Napoleon III served his most honorary guests with aluminum tableware and dreamed of supplying his army with cuirasses – armor, breastplates and back plates – made of the lightweight metal.⁹⁰ In 1856, Wohler designed a toy rattle for Napoleon III's son, Crown Prince Louis Napoleon, made of aluminum and gold. Napoleon III used aluminum for medals, ornaments and luxury items. Deville, however, believed that the future of aluminum was not just

jewelry and luxury items. “There is nothing harder than to make people use a new metal,” he said. “Luxury items and ornaments cannot be the only sphere of its application. I hope the time will come when aluminum will serve to satisfy the daily needs.”⁹¹

The first aluminum plant

Deville was the first person to produce commercial quantities of aluminum, using a pilot plant built near Paris.⁹² He described an early aluminum ingot as “a white metal, unalterable like silver... with the unique property of being lighter than glass.”⁹³ Able to produce aluminum in pieces the size of marbles, Deville immediately brought the price down to \$1,300 per pound. Napoleon III demanded that an effort be made to find a way to mass produce the metal for military purposes, and Deville was commissioned to study the problem. By 1859, the price of aluminum had been brought down to about \$245 per pound, but the chemical methods used to extract aluminum from bauxite were too expensive for mass production. At the same time, the industrial revolution was in full swing and the need for a metal like aluminum was being recognized.⁹⁴ Deville’s improvements also aroused the interest of the French Academy, which contributed 3,000 francs toward further research into producing metallic aluminum. The experiments continued at the Javel Chemical Works, where bars of aluminum were eventually produced. Deville then joined forces with Debray, Morin and Rousseau Brothers in Glaciere, a suburb of Paris, where they ran into trouble with neighbors who objected to the smell of chlorine and salt fumes emitted from the plant. Before moving the pilot plant to Nanterre, the Glaciere operation had succeeded in lowering the cost of aluminum to \$389 per pound, but Deville had succeeded in producing only about 60 pounds of aluminum.⁹⁵

Deville was born on the island of St. Thomas, West Indies in 1818 and died in Boulogne-sur-Seine, France in 1881. He was educated in Paris, graduated as a doctor of medicine and science in 1844 and became a professor at the Sorbonne in 1859.⁹⁶ He harshly criticized the Tissier brothers’ 1858 publication on aluminum production – the Tissiers were young chemists Deville had invited into his laboratory and who allegedly unfairly used his ideas. Deville responded in 1859 by publishing a major text of his own on aluminum, a 176-page book titled “De l’Aluminium, ses Proprietes, sa Fabrication et ses Applications.” The book concluded with a 12-page chapter describing possible future uses for aluminum metal. Deville also discussed the use of fluoride salts rather than chloride salts as fluxes. He stated that cryolite was the better flux, but that fluorspar was much cheaper. When the cost of cryolite dropped to about \$1,082 per ton, Deville substituted it for fluorspar.⁹⁷

Deville recognized that alumina dissolved in molten cryolite in 1859 – a key component of modern aluminum smelting – but during an 1893 U.S. patent infringement suit, Judge William Howard Taft credited Charles Martin Hall with making this discovery. Deville’s discovery, however, had been mentioned in several academic chemistry texts, including one by Wurtz in 1868 and one by Payen in 1878.⁹⁸ In April 1859, *Scientific American* reported that advances in the production of aluminum using cryolite from the west coast of Greenland had brought the price of aluminum down by a factor of 18 since 1856. The magazine also reported that M. Gerhard was using the “aluminous mineral” to produce aluminum metal at a large factory recently constructed at Battersea, England. As the production cost of aluminum dropped, the idea arose to use aluminum for making coins.⁹⁹

A typical charge in Deville’s process included 10 parts aluminum-sodium chloride, five parts fluorspar and two parts sodium ingot. The mixture was heated in a reverberatory furnace, sealed from the atmosphere, and produced from 6 to 10 kilos of aluminum metal at a time. By 1859, this process had further reduced the cost of aluminum production to about \$245 per pound. Further reductions in the cost of aluminum production by this process depended upon the development of cheaper ways to produce sodium metal. This did not take place until 1886, when Hamilton Y. Castner of New York patented an important process for reducing sodium hydroxide using iron carbide.¹⁰⁰ The first practical combination of the Deville and Castner processes was made by the Aluminium Co. Ltd. of Oldbury, near Birmingham, England, beginning in 1888. By 1889, the company was producing 500 pounds of aluminum metal per day. At this point in time, the best commercial way to produce aluminum metal was by use of the Deville and Castner methods, but scores of scientists and others were investigating different processes, including the use of cryolite in place of aluminum chloride or using the double chloride of sodium and aluminum. Drawbacks to using cryolite were its higher melting temperature, which required burning more fuel to heat the crucible; its high reactivity, which led to the cryolite attacking the crucible walls and contaminating the charge with silica; and its high cost and uncertain supply at that time.¹⁰¹

“There are several reasons why the metal is shown so little favor,” Clemen Winckler wrote about advances in aluminum production in *Scientific American* in 1879. “First of all, there is the price; then, the methods of working it are not everywhere known; and further, no one knows how to cast it.” The sodium reduction process produced metal with an erratic chemical composition, despite the four-part melting process Deville had developed to purify the metal.¹⁰² But the bigger problem was the discovery of the Hall-Heroult electrolytic process in 1886, which spelled the end of aluminum production by strictly chemical means. The electrolytic process for producing aluminum from alumina was investigated in 1854 by Robert Wilhelm von Bunsen. Working in Heidelberg,

Germany, Bunsen prepared aluminum metal by passing an electric current through a fusion of sodium-aluminum chloride. In his electrolysis experiments, Bunsen had succeeded earlier in producing magnesium from magnesium chloride. Following up on Bunsen's experiments, Deville also used electrical current to produce aluminum metal. But both scientists depended upon batteries for electrical current, an expensive method with no commercial future. Another 25 years would pass before electrical dynamos were perfected and electrical power was sufficiently inexpensive for commercial purposes.¹⁰³

In 1855, a young chemical engineer named Henri Merle received permission from Napoleon III to establish a plant at Salindres, near Alais in the Gard region of France, to produce caustic soda from coal, salt, pyrites and limestone. The new company, owned by Merle and operated by Jean-Baptiste Guimet, began to produce aluminum metal in 1860 using Deville's chemical method under a 30-year monopoly granted by the French government. Compagnie de Produits Chimiques d'Alais et de la Camargue produced 505 kilograms of aluminum in its first year. Aluminum at the time was an expensive luxury item, and the company offered aluminum cutlery to Napoleon III as a wedding gift.¹⁰⁴ All the raw materials used in the Deville process were found near Salindres, including coal, soda, hydrochloric acid and bauxite, which had been discovered in Provence in 1821. The Salindres plant stopped manufacturing aluminum in 1888 after reaching a maximum production of 9,160 pounds in one year.¹⁰⁵ Alfred Rangod, who went by the name A.R. Pechiney, joined the company in 1874 and was a long-term managing director. Over time, the company became known as Pechiney.¹⁰⁶ Pechiney, who managed the company from 1877 to 1906, passed up a chance to use the Hall-Heroult electrolytic process until 1897.¹⁰⁷

Deville's success in producing aluminum in commercial amounts had an impact on the public's imagination. Commenting in his weekly English magazine "Household Words" on Dec. 13, 1856, Charles Dickens wrote, "Aluminium may probably send tin to the right about face, drive copper saucepans into penal servitude, and blow up German-silver sky high into nothing." In his 1865 science-fiction novel "From The Earth To The Moon," French writer Jules Verne chose aluminum for construction of the capsule shot from the cannon on Earth because of its lightness and strength.¹⁰⁸ By 1869, processes for producing aluminum by chemical reaction and precipitation had improved to the point that world production reached about two tons of aluminum metal per year and the cost dropped to about the same as silver. Aluminum was the reasonable choice for making tableware for the French court, a crown for the King of Denmark and the cap on the Washington Monument in Washington, D.C.¹⁰⁹ But there were some in industry who saw an important future for aluminum. In 1884, William Frishmuth, who supplied the

aluminum for capping the Washington Monument, warned in the New York Times that “foreign capitalists” were about to control the global aluminum market.¹¹⁰

America’s crown jewel

The history of the Washington Monument began in 1783 when the Continental Congress passed a resolution to create an equestrian statue in the memory of George Washington, but the plan changed over time. The cornerstone for the Washington Monument was laid in 1848 and the monument was completed and dedicated in 1885. At 169.1 meters high, it was the tallest man-made structure in the world at the time. Aluminum was not the first choice for the cap and was considered an alternative during discussions with Frishmuth, the only aluminum producer in the U.S. at the time. Using Deville’s method with some refinements, Frishmuth produced 51 kilograms of aluminum in 1884. The next year, he produced 28 kilograms.¹¹¹ Aluminum was chosen for the cap because of its conductivity, color and non-staining qualities. Col. Thomas Casey, the Army Corps of Engineers officer in charge of seeing the monument’s completion, had asked Frishmuth to make a metal pyramid to serve as a lightning rod. Copper, bronze or brass, plated with platinum, were the preferred materials. Frishmuth proposed constructing the pyramid of aluminum for \$75. If unsuccessful in that endeavor, he would make a pyramid of aluminum bronze and plate it with gold for \$50.

¹¹²

Aluminum bronze was an alloy made of 90 parts copper and 10 parts aluminum and was quite abundant on the market by 1884. The principal manufacturer of aluminum bronze was the Cowles Brothers, of Niagara Falls, N.Y., which used a patented thermal process using an electrical-resistance furnace and a raw material containing aluminum oxide and copper. The aluminum produced this way combined with copper and could not be separated from it. When Frishmuth submitted his \$256 bill for the all-aluminum pyramid, Casey was quite upset and sent Capt. Davis to Philadelphia to investigate the matter. After Davis conducted an audit, a final bill of \$225 was agreed upon between Casey and Frishmuth.¹¹³ The gleaming pyramid of aluminum metal topped with eight platinum lightning rods was placed on the monument in 1884. At 100 ounces, it was one of the largest pieces of aluminum ever assembled. Prior to its placement, the pyramid sat in a window at Tiffany’s in New York City, and the New York Times prophesied that “the uses of the metal are almost illimitable.”¹¹⁴

On June 8, 1885, during a thunderstorm, a lightning strike caused a crack in the north face of the “pyramidion” atop the monument. In 1934, a group of scientists inspected the cap and discovered that lightning strikes had blunted the tip of the pyramid and some globules of aluminum had fused to the sides. Edgar H. Dix, Alcoa’s chief

metallurgist, declared at the time that “the crown jewel of the aluminum industry is the cap of the Washington Monument.” The pyramid was 22.6 centimeters high and 13.9 centimeters at the base and weighed 2.85 kilograms. The size of the casting was one achievement, the quality was another. With no knowledge of dissolved gases in aluminum, Frishmuth nonetheless was able to create a homogeneous casting that could be polished and leave a smooth surface. The cap was found to be 1% iron, 0.75% silicon, 0.3% manganese, 0.05% copper, 0.02% tin, 0.01% sodium and 97.87% aluminum. A 100-year commemorative celebration of the casting was held at the Frishmuth building in Philadelphia, which was still operating as a foundry. A replica of the pyramid, exact in size, weight and composition, was cast on Nov. 12, 1984, and displayed at Tiffany’s in New York.¹¹⁵

By 1887, the price for aluminum had dropped to about \$115 per pound, but less than 140,000 pounds had been produced since 1854. Most uses included jewelry, navigation instruments and clocks.¹¹⁶ In 1893, an aluminum statue of the ancient Greek god Anteros was placed in Piccadilly Circus, London. The Deville-Process cast statue was nearly 2.5 meters high and was the first large piece of art made from aluminum.¹¹⁷ But the days of producing aluminum by chemical means alone were numbered following the 1886 discovery of the Hall-Heroult process – which depended on large reliable sources of electrical power, cryolite and alumina.

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